NASA Technical Memorandum 108811

An Investigation of Acoustic Noise Requirements for the Space Station Centrifuge Facility

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Summary

Acoustic noise emissions from the Space Station Freedom (SSF) centrifuge facility hardware represent a potential technical and programmatic risk to the project. The SSF program requires that no payload exceed a Noise Criterion 40 (NC-40) noise contour in any octave band between 63 Hz and 8 kHz as measured 2 feet from the equipment item. Past experience with life science experiment hardware indicates that this requirement will be difficult to meet. The crew has found noise levels on Spacelab flights to be unacceptably high. Many past Ames Spacelab life science payloads have required waivers because of excessive noise.

The objectives of this study were (1) to develop an understanding of acoustic measurement theory, instruments, and technique and (2) to characterize the noise emission of analogous Facility components and previously flown flight hardware.

Test results from existing hardware were reviewed and analyzed. Measurements of the spectral and intensity characteristics of fans and other rotating machinery were performed. The literature was reviewed and contacts were made with NASA and industry organizations concerned with or performing research on noise control.

Nomenclature

AAA	avionics air assembly
ACF	animal care facility
AEM	animal enclosure module
CFP	Centrifuge Facility Project
FSS	flight system specification
IL	insertion loss
NA	not applicable
NM	not measured
NR	no requirement
SPL	sound pressure level
SSF	Space Station Freedom

Introduction

The centrifuge facility will operate within the confines of Space Station Freedom (SSF). Crew will be present continuously for at least 90 days. NASA has set relatively stringent acoustic emission requirements for all hardware within the crew habitable area of SSF.

Centrifuge Facility Overview

There are several probable sources of noise within the Centrifuge Facility Project (CFP) hardware that merit discussion:

Life support– The CFP hardware is designed to enable experiments on plants and rodents in a zero-g environment and to provide artificial gravity by use of a centrifuge at selectable gravity levels. As such the facility will provide life support and environmental control for the specimens that are to some extent independent from those provided to the crew in the SSF cabin. This environmental control requires airflow. The generation of airflow invariably produces some acoustic noise.

Bioisolation– The animals and plants are required to be “bioisolated” from the crew living environment. One likely means of bioisolation is the maintenance of specimen environments at a small negative pressure relative to the cabin. This pressure differential can be provided by airflow.

Centrifugation– The artificial gravity is provided by a large centrifuge on which specimens can be housed for long periods. The centrifuge rotor will be rotating within the cabin air with tangential velocities as high as 5 m/s (11.2 mph). Some noise is inevitable.

Air exchange during transport– The CFP-provided rodent transporter (used to bring experimental subjects from the launch site to orbit) will be designed to fit within a shuttle orbiter middeck locker. The transporter must exchange air within the cabin to maintain the specimen living environment.

In addition to fans, there are other likely sources of continuous noise such as air/liquid separators, electric motors, and pumps. They will not be discussed here. Intermittent sources of noise such as relays and motor driven mechanisms will likewise not be discussed in this report.

Overview of SSF Acoustic Requirements

The SSF program requires that no payload exceed an NC-40 noise contour in any octave band between 63 Hz and 8 kHz as measured 2 feet from the equipment item (Payload Accommodation Handbook SS-HDBK-001, October 30, 1992, p. 7-16). This requirement is identical to the current Spacelab acoustic requirement (ref. 1).

Overview of Space Shuttle Middeck Acoustic Requirements

The shuttle middeck has its own payload acoustic noise emission requirements that are different in philosophy from those of SSF and Spacelab. They are based on the known middeck noise environment less 10 dB and not on any human perception or speech interference guidelines.

Historical Justification

Past flight experience has revealed that many payloads and vehicle systems have done a poor job of acoustic design and as a result are unnecessarily noisy. Acoustics has traditionally not been treated as a systems issue and therefore has not been considered early in the design process. Acoustic problems are often not discovered until verification testing. At this point all that can be done are "band-aid" fixes (such as sound absorbing coverings) or applying for a waiver of the requirement. The net result is a very loud working environment for the astronaut crew. On short duration shuttle missions the noise has been tolerable, but inconvenient. On much longer duration SSF increments, these high levels of noise will be intolerable and not allowed.

Acoustics Fundamentals

Acoustics is the science of sound. Sound is a disturbance that propagates through an elastic medium at a speed characteristic of that medium (ref. 2). At room temperature the speed of sound in air is about 340 m/s. Since sound involves the propagation of longitudinal compression waves, the wavelength, λ, can be calculated like any other wave phenomenon.

$$\lambda = \frac{c}{f} \tag{1}$$

where c is the speed of sound in the medium of interest (always air for our purposes) and f is the frequency. The range of normal adult human hearing extends from 20 Hz to 20,000 Hz. This corresponds to a range of wavelengths from 17 meters to 21 millimeters.

Since sound is a wave phenomenon, all the properties of waves apply to sound. Diffraction, refraction, reflection, and absorption can occur. The amount of each can depend on the wavelength.

Sound Pressure Levels and Decibels

"The physical quantity that is generally of interest is sound pressure, the incremental variation in pressure above and below the ambient pressure" (ref. 2). The customary measure of sound pressure level is the decibel. Sound pressure level (SPL) in dB is defined as:

$$\mathrm{SPL\,(dB)} = 20 \log \frac{P}{P_o} \tag{2}$$

where $P_o = 2 \times 10^{-5}$ N/m^2 (pascals), the logarithm is base 10, and P is the measured sound pressure. P_o is "the threshold of hearing at 1,000 Hz for a young listener with acute hearing, measured under laboratory conditions" (ref. 2). This is a peak amplitude based measurement, not a root mean square based measurement.

Since the dB scale is logarithmic, small changes in SPL dB level correspond to large increases in noise. A 3 dB difference is generally considered to be imperceptible to a human listener. A +10 dB difference is generally perceived as being twice as loud. If a noise specification is exceeded by 10 dB, this means that the source produces variations in sound pressure magnitude three times what is allowed. This is a huge nonconformance. To illustrate this, imagine a spacecraft that weighs three times what it should or a wall outlet that provides 330 volts when 110 are expected.

Octave Band Measurements

An octave is a span of frequencies whose upper and lower bounds differ by a factor of 2. The lower cutoff frequency is one-half the upper cutoff frequency, as shown in table 1. It is the customary way to partition the audio spectrum.

Table 1. Standard full octave bands (Hz)

Octave band center frequency	Lower cutoff frequency	Upper cutoff frequency
31.5	22.3	44.6
63	44.6	88.4
125	88.4	177
250	177	354
500	354	707
1,000	707	1,414
2,000	1,414	2,828
4,000	2,828	5,656
8,000	5,656	11,310
16,000	11,310	22,620

Adapted from reference 2.

No frequencies below 22.3 Hz or above 22,620 Hz are included in these standard full octave bands because this is beyond the range of human hearing.

The span of frequencies included in an octave band doubles from one octave band to the next octave band.

This fact is important to remember when comparing octave band noise levels. For example, an octave band analysis of white noise (noise that has the same intensity at all frequencies) shows an increase of 3 dB in octave band dB level for each step in octave band toward the higher frequencies. This is not because the SPL at each frequency is greater at higher frequencies (remember the definition of white), but because the octave bands over which the SPLs are measured are wider at higher frequencies.

Narrow Band Measurements

It is also possible to measure the spectrum in bands that are much narrower than an octave. This is useful in identifying specific sources of noise. Half-, one-third, or one-twelfth octaves are common. For example, some fans emit noise at a particular frequency determined by the fan rotation rate and the number of fan blades. If this information is known about a particular fan, its contribution to the overall noise level can be identified through a narrow band measurement and the observations of peaks at the suspected frequencies. These peaks would not be identifiable in a full octave measurement because of the fundamental lack of resolution inherent in such a broad band measurement.

Human Hearing Response

The human ear is sensitive (nominally) from 50 Hz to 20,000 Hz. See figure 1 for the threshold of hearing in dB versus frequency for an average human. Peak sensitivity occurs at about 4,000 Hz and the threshold of hearing can vary as much as 60 dB from this at the lower frequencies. This lack of sensitivity at low frequencies is an important factor in the development of “noise criterion,” which will be discussed later.

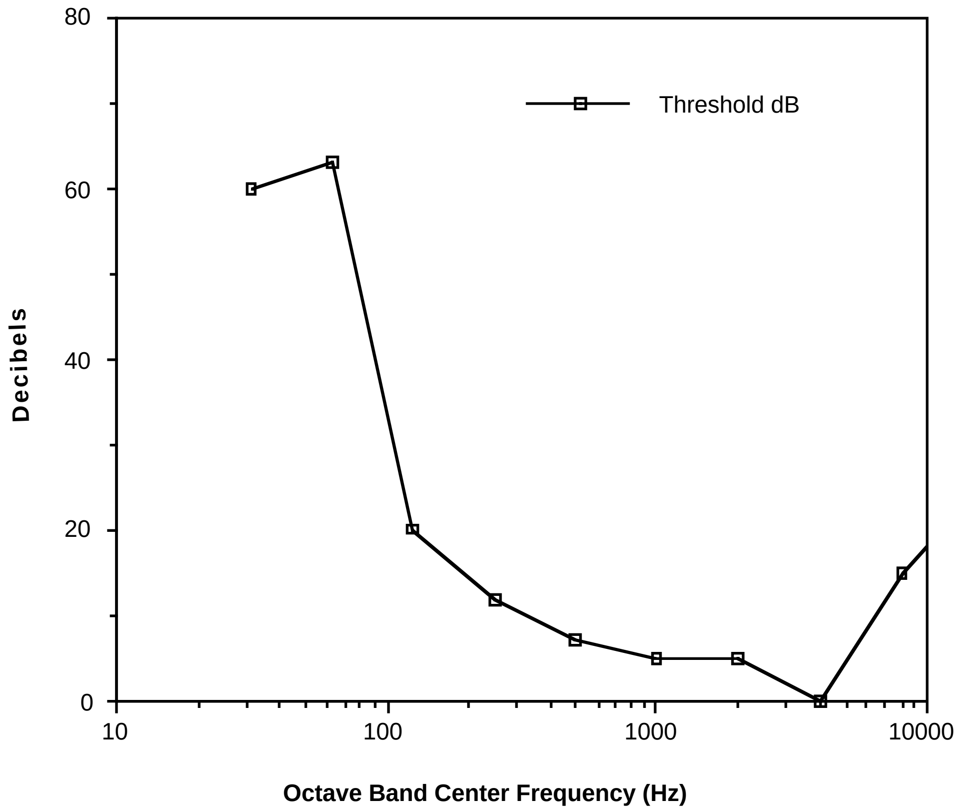

Figure 1. Human threshold of hearing.

Weighting Scales

Several weighting scales have been developed that permit simplification of frequency versus intensity measurements into a single loudness number. As with most simplifications, some information is lost. That is, there are many spectral shapes that have the same overall perceived loudness. Most common of the weighting scales is the dB(A) scale, which is built into many sound level meters. It is designed to approximate the response of the human ear, but necessarily smooths any abrupt changes in sensitivity as a function of frequency.

The dB(A) scale is reproduced in table 2 and is represented graphically in figure 2. To convert from all-pass measurements to a single A-weighted measurement, one must measure the SPLs in the standard octave bands and apply the following weighting function (an addition to each octave band). The result is then summed (by the method described later for the addition of multiple sources of different frequencies) to result in a dB(A) number.

Observe that the weighting function has little effect for octave frequency bands from 1,000 to 8,000 Hz.

Table 2. A-weighting scale

Octave band	dB
31.5	–39.4
63	–26.2
125	–16.1
250	–8.6
500	–3.2
1,000	0
2,000	1.2
4,000	1
8,000	–1.1
16,000	–6.6

Adapted from reference 2.

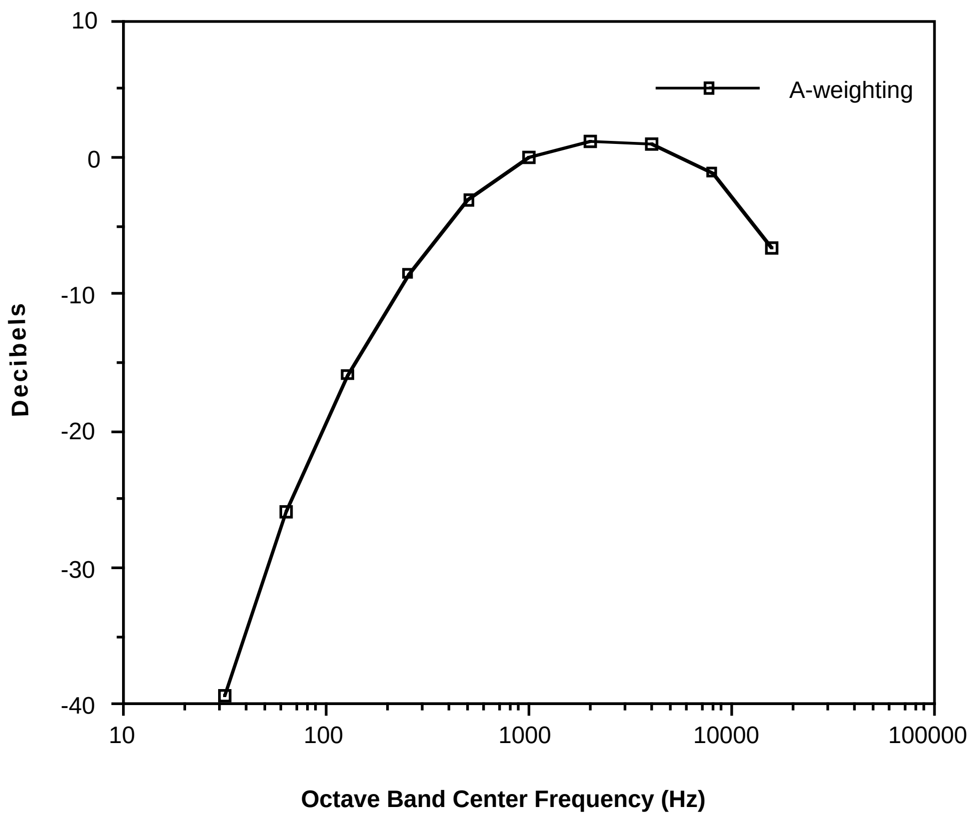

Figure 2. A-weighting scale (adapted from ref. 2).

Noise Criterion Curves

Noise criterion (NC) curves were developed to specify environmental noise levels that permit intelligible speech between humans in work environments. As such, they are based on both the response of the human ear and the spectral intensity of human conversation. A component or environment is said to meet a specified NC level if no octave band SPL emission of that component or environment exceeds that specified by the NC curve. Because of this “no exceedance” criterion there is *no* exact correspondence between the NC level of a component or an environment and its overall SPL dB or dB(A).

A good “rule of thumb” is that an NC curve crosses its own level at 1,500 Hz. For example, an NC-40 curve has a value of approximately 40 dB at 1,000 Hz. Similarly, an NC-50 curve has a value of approximately 50 dB at 1,000 Hz. Table 3 lists the dB levels allowed for each octave by the NC-40 standard. Figure 3 presents the same information graphically (adapted from ref. 3).

Table 3. NC-40 levels

Octave band	dB max*
31.5	NR
63	64
125	56
250	50
500	45
1,000	41
2,000	39
4,000	38
8,000	37
16,000	NR

*Maximun sound pressure level measured in dB within an octave band.

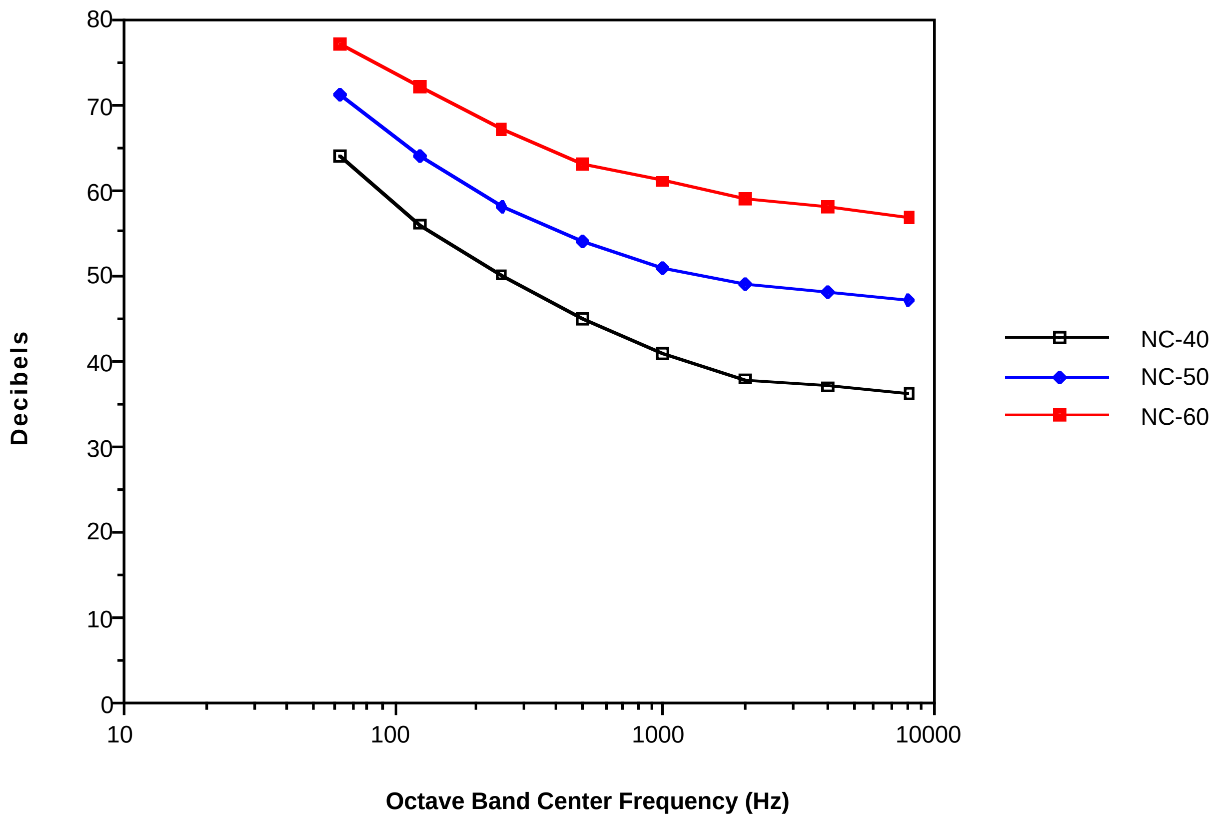

Figure 3. Noise criterion curves.

Addition of Sound Pressure Levels of Multiple Sources

The combined SPL of two uncorrelated sources, P_1 and P_2, of equal loudness, equidistant from an observer, is determined by

$$
\begin{aligned}
\text{SPL (dB)} &= 20 \log \sqrt{P_1^2 + P_1^2} \\
\text{SPL (dB)} &= 20 \log \sqrt{2}\left(P_1\right)
\end{aligned}
\tag{3}
$$

The resulting SPL will be 20 times the log of $\sqrt{2}$ (0.1505), or 3 dB above P_1.

> Two equal loudness sources are together 3 dB louder than one source alone.

Correction for Background Noise Levels

"If in any frequency band the difference between the background noise level and the source noise level is greater than 10 dB, the background levels will not significantly affect measurement of the source noise" (ref. 2). This is because a 10 dB (logarithm) difference corresponds to a difference in SPL of a factor of 3 (linear). If the difference is less than 10 dB, table 4 (from ref. 2) can be used.

Table 4. Background subtraction

Difference between total and background	dB to be subtracted from total to get source dB
8–10	0.5
6–8	1.0
4.5–6	1.5
4–4.5	2.0
3.5	2.5
3	3.0

When the difference between the total and the background is 3 dB, the source and the background are of equal loudness.

> Sound measurements need only to be made in an environment that is quiet enough (more than 3 dB below the item to be measured if background subtraction can be performed, or 10 dB below the item to be measured to make subtraction unnecessary). Acoustic chambers are justified only for the testing of sources that are expected to be very quiet.

Addition of Sound Pressure Levels of Multiple Octave Band Measurements

Often it is useful to determine an overall SPL or a dB(A) level from individual octave band measurements. Since SPLs are just pressure measurements, the overall pressure is just the square root of the sum of the squares of the SPLs of the octave band measurements (principle of superposition for linear systems and sinusoidal signals). The subtlety is that SPLs are in decibels, which must be converted back to pressures, added, and the result converted back to dB. Equation (3) will work for any number of sources. See reference 2 for a detailed procedure.

In the appendix there is a paragraph from SS-HDBK-001 entitled Design Guidance. It is reproduced here for clarity.

> 5.9.5.1.2 **Design Guidance** The Acoustic noise of all equipment (systems plus payloads) shall not exceed the noise rating curve NC-50 of the United States Noise Standard. *This means that a payload should make every effort to be as far below the NC-40 curve as possible because it takes so few equipment items at the allowable NC-40 curve to have the total noise spectrum exceed the NC-50 curve.* A considerable redesign effort may be required to reduce noise levels when this situation occurs. (italics mine)

It can be shown (by using the method described in the section entitled Addition of Sound Pressure Level of Multiple Sources) that a 9 dB increase in overall sound level will result from eight equal-loudness, uncorrelated sources. The second equal-loudness source increases the overall SPL by 3 dB; to add three more dB requires four total equal-loudness sources; another 3 dB requires eight total equal-loudness sources, and so forth.

> Eight payloads that meet NC-40 individually will together be 9 dB louder than each individually, and hence just meet NC-50.

This addition method neglects distance effects, diffraction, and attenuation and is therefore applicable only in a highly reverberant environment. The near-complete absence of fabrics or "furnishings" may allow the SSF interior to approach the acoustic characteristics of an empty house (i.e., highly reverberant). This method gives an order of magnitude estimate of the effect of multiple sources and together with the design guidance above makes it clear that it is in the CFP's interest to produce quiet hardware—perhaps quieter than NC-40.

Effect of Distance on Sound Pressure Level

A doubling of distance from a noise source (in the free field) will reduce to one-half the SPL measured by an observer (by 1/r) (ref. 2). Since the SPL decibel scale is based on

$$\mathrm{SPL} = 20 \log \frac{P_2}{P_1}$$

in this case

$$P_2 = \frac{P_1}{2}$$

then

$$\mathrm{SPL} = 20 \log \frac{1}{2} P_1$$

The resulting decrease in SPL will be 20 times the log of 0.50 (which is –0.301), or –6 dB.

A doubling of distance reduces the measured SPL by 6 dB.

Because of this rapid fall-off with distance, noise source SPL measurements that do not state at what distance the measurements were made are meaningless.

Free Field Versus Reverberant Environment

In a highly reflecting environment the sound pressure level may not decrease with distance from a noise source, because all sound waves are reflected from the reflecting walls back toward the source. This contrasts with a sound measurement made in an open environment, in which the sound waves travel past the observer only once and never return.

Testing

One of the main objectives of this study is to develop a "hands on" understanding of acoustics measurement techniques and instruments. The subject under test was not as important as the lessons learned from the testing itself. Consequently, measurements were made of the acoustic noise of familiar, easily accessible environments.

Ambient Noise Measurement

A General Radio Model 1558 BP octave band noise analyzer (vintage 1968) was used to measure the SPL in 10 full octave bands. The overall SPL and the A-weighted, or dB(A), SPL were measured in several locations in Building 244 of Ames Research Center. The ambient sound levels in a typical office, shop area (high bay), and computer room were measured. The meter, run from an internal battery, was carried into the room to be measured; the microphone was oriented randomly; and octave band, A-weighted, and overall SPL were recorded with paper and pencil. No effort was made to control the sources of noise (e.g., people, machines). The results are shown in tables 5–7 and figures 4–6.

Table 5. Bldg. 244 high bay noise levels

Octave band	dB
31.5	61
63	59
125	55
250	52
500	53
1,000	52
2,000	54
4,000	51
8,000	46
16,000	<45
Overall	NM (65.2*)
A-weighted	59 dB(A)

*Calculated overall SPL based on measured octave band levels.

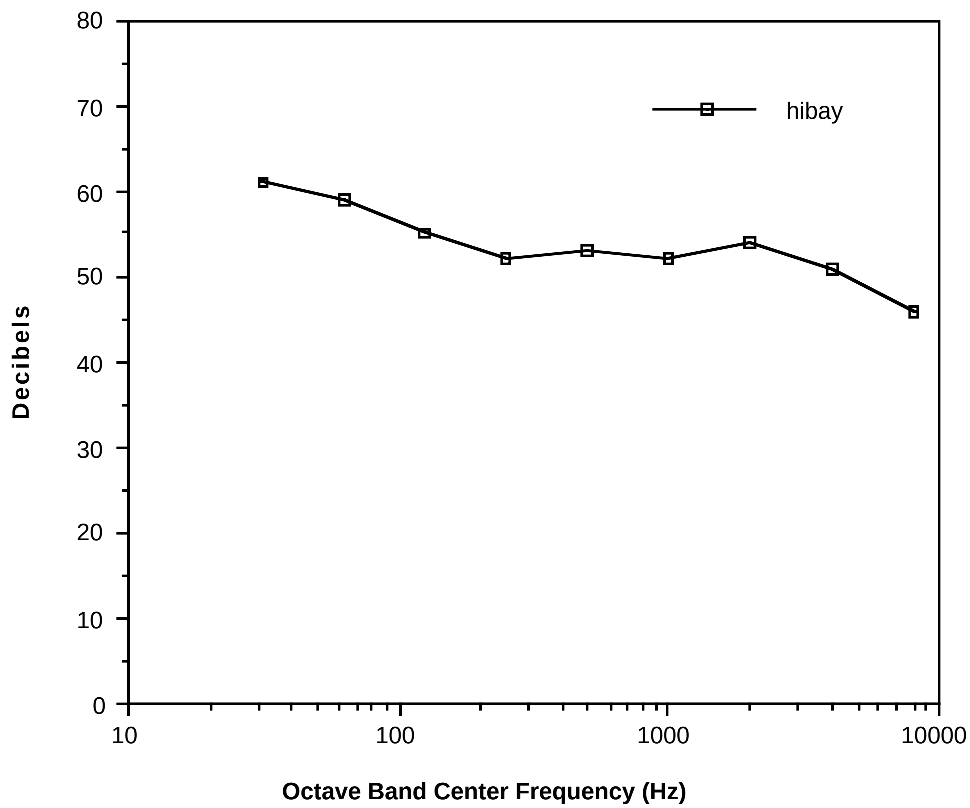

Figure 4. Bldg. 244 high bay noise levels.

Table 6. Bldg. 244, Rm. 217 office noise level

Octave band	dB
31.5	64
63	55
125	45
250	45
500	<45
1,000	<45
2,000	<45
4,000	<45
8,000	<45
16,000	<45
Overall SPL	NM (64.8*)
A-weighted	44 dB(A)

*Calculated overall SPL based on measured octave band levels.

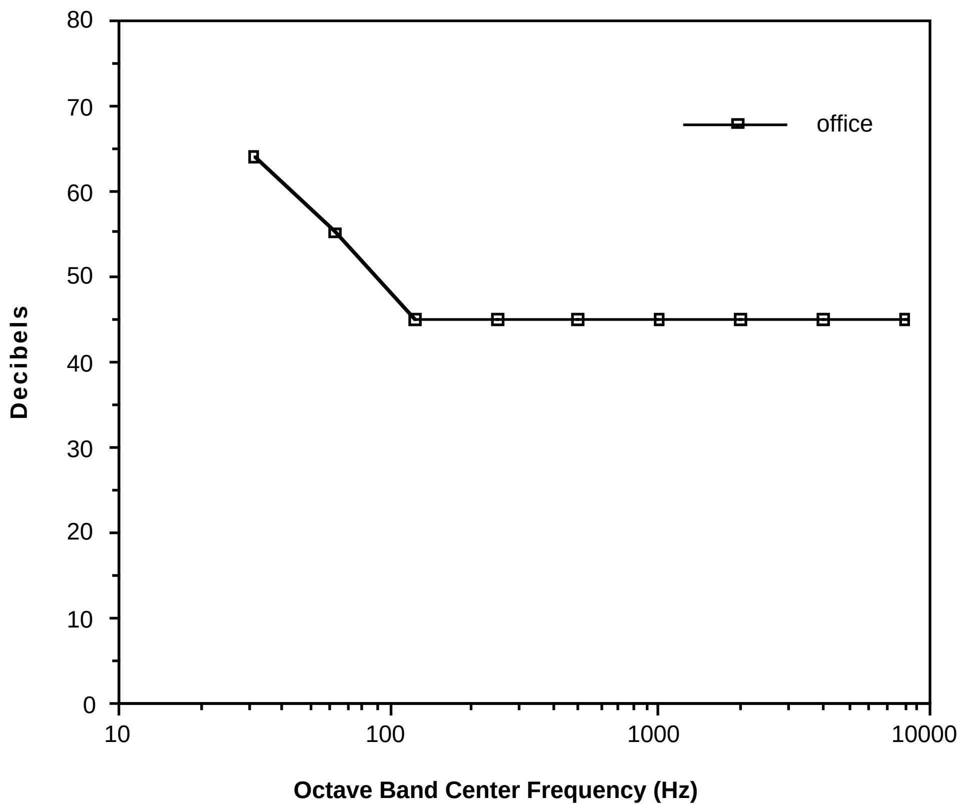

Figure 5. Bldg. 244, Rm. 217 office noise levels.

Table 7. Bldg. 244, Rm. 105 computer room noise levels

Octave band	dB
31.5	54
63	50
125	62
250	67
500	57
1,000	52
2,000	46
4,000	<45
8,000	<45
16,000	<45
Overall SPL	69 dB
A-weighted	60 dB(A)

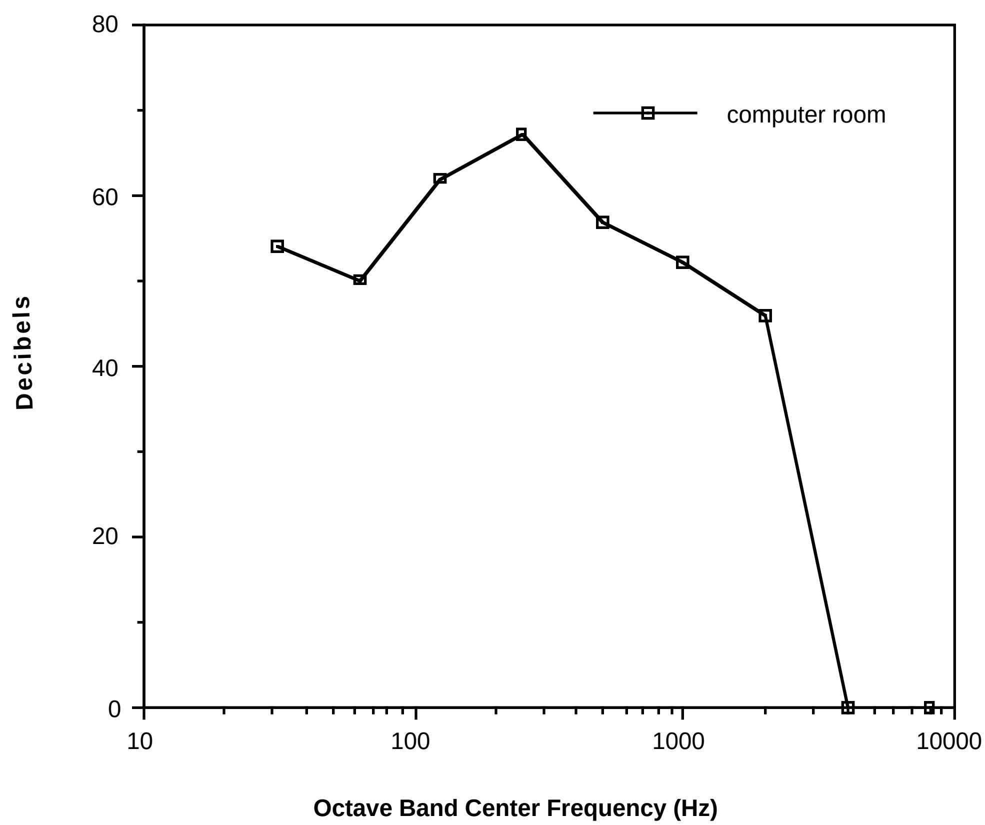

Figure 6. Bldg. 244, Rm. 105 computer room noise levels.

Results of Ambient Noise Measurement Testing

> From figure 7 it can be seen that the SSF acoustic requirement imposed on payloads results in a noise environment that is more typical of an office than it is of a laboratory or a computer room.

Both the computer room and the high bay exceed the NC-40 contour by more than 10 dB at several octave bands. It can be shown that the computer room meets only NC-60 and that the high bay meets only NC-55.

Prototype Animal Enclosure Module Testing

Sound pressure level measurements were made of both the interior and exterior of a prototype animal enclosure module (AEM) that is acoustically if not physically similar to the unit that flew on Space Life Sciences 1 (SLS-1), a shuttle flight dedicated to life science research that took place in June 1991. A General Radio Model 1558 BP octave band noise analyzer was used to measure the sound pressure levels in 10 full octave bands. The CFP rodent habitat may require airflow volume similar to an AEM and therefore could, if not controlled, have comparable acoustic emissions. By measuring an AEM, some familiarity with the features of habitat designs that affect noise might be obtained.

The only sources of noise in an AEM are the four large fans in the face of the unit. Measurements were made inside the specimen chamber and at 1 foot and 2 feet from the face of the unit (shown in tables 8–10 and figures 8–10). A background noise measurement was made with the fans off. The background was sufficiently low and was neglected.

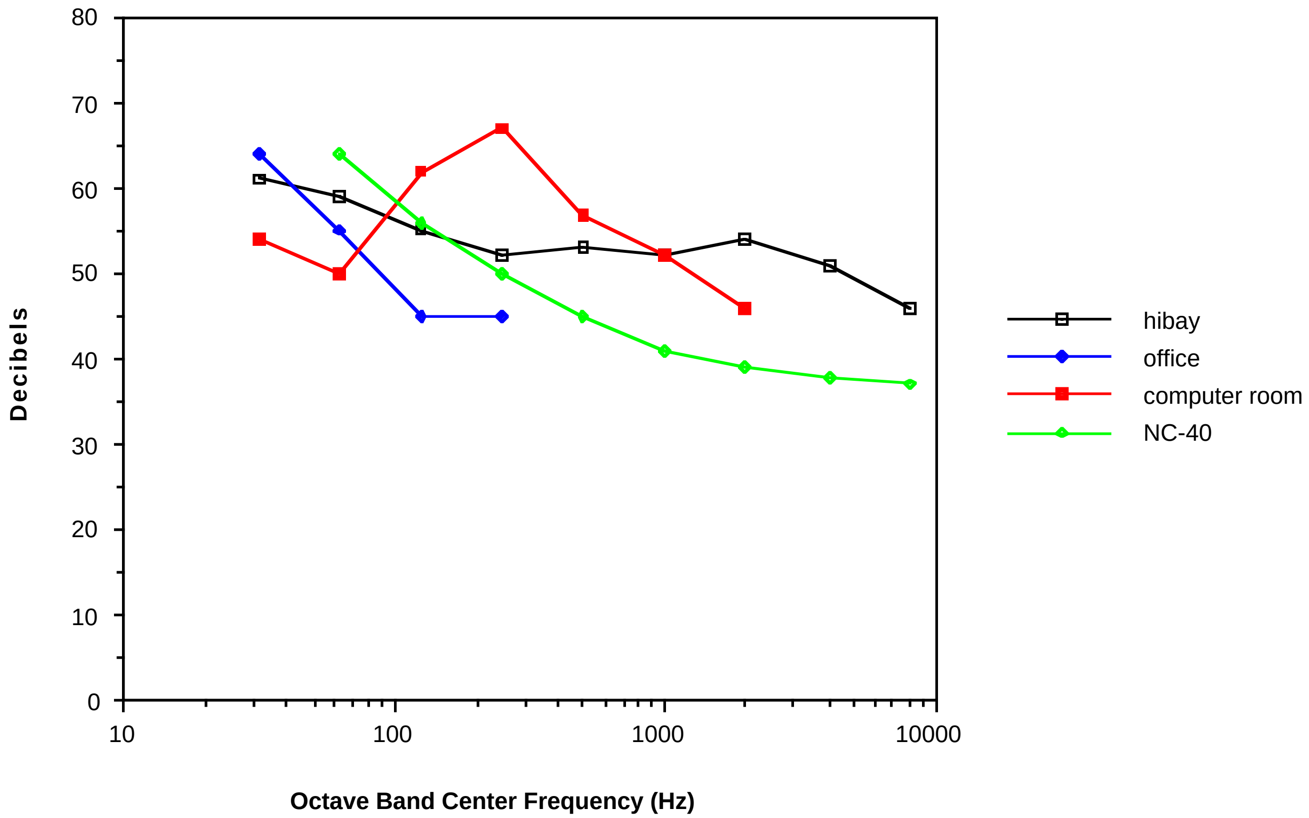

Figure 7. Comparison of SSF requirement against Bldg. 244 locations.

Table 8. AEM prototype interior noise levels

Octave band	dB
31.5	58
63	68
125	74
250	71
500	62
1,000	61
2,000	58
4,000	45
8,000	<45
16,000	<45
Overall	77 dB
A-weighted	66 dB(A)

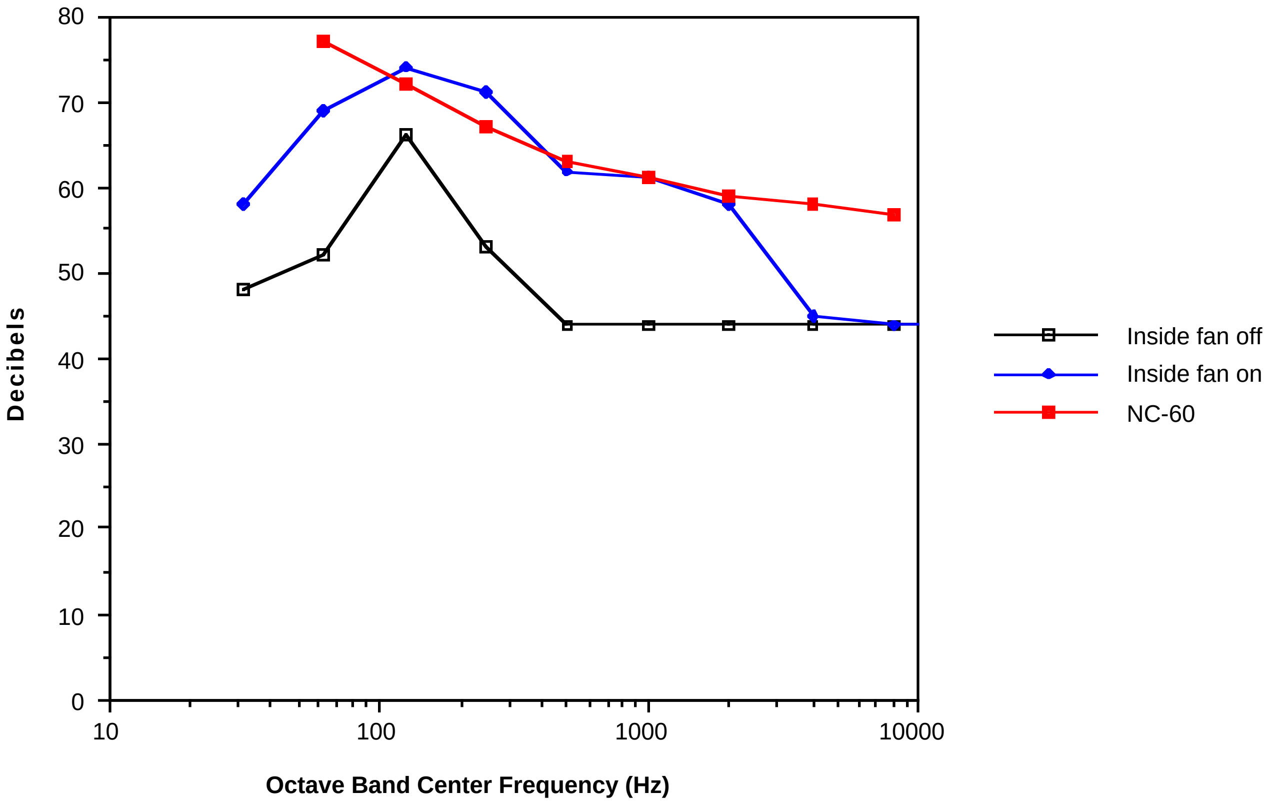

Figure 8. AEM prototype interior noise levels.

Table 9. AEM prototype exterior noise levels at 1 foot

Octave band	dB
31.5	73
63	70
125	65
250	63
500	63
1,000	63
2,000	63
4,000	57
8,000	54
16,000	54
Overall SPL	78 dB
A-weighted	68 dB(A)

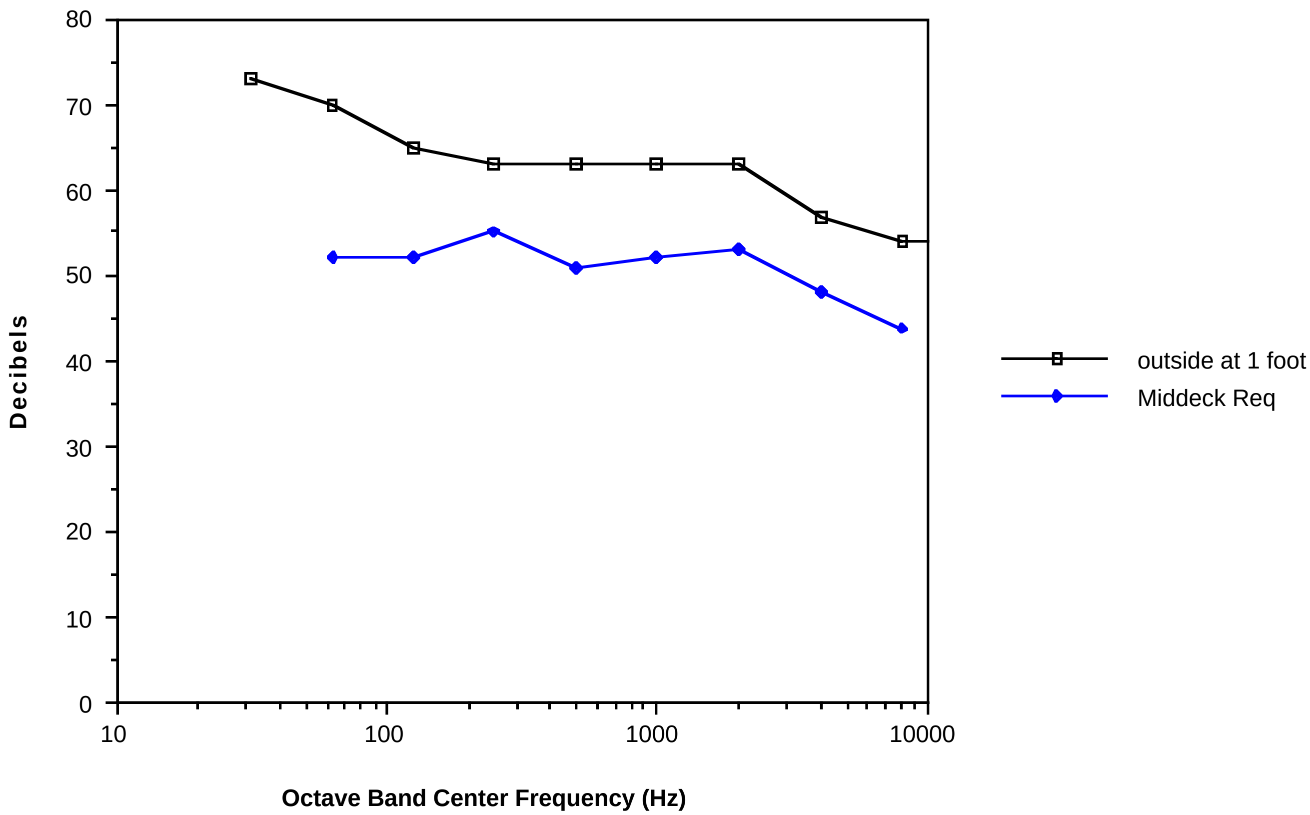

Figure 9. AEM prototype exterior noise levels at 1 foot.

Table 10. AEM prototype exterior noise levels at 2 feet

Octave band	dB
31.5	64
63	68
125	64
250	59
500	60
1,000	60
2,000	55
4,000	52
8,000	50
16,000	<45
Overall SPL	70 dB
A-weighted	64 dB(A)

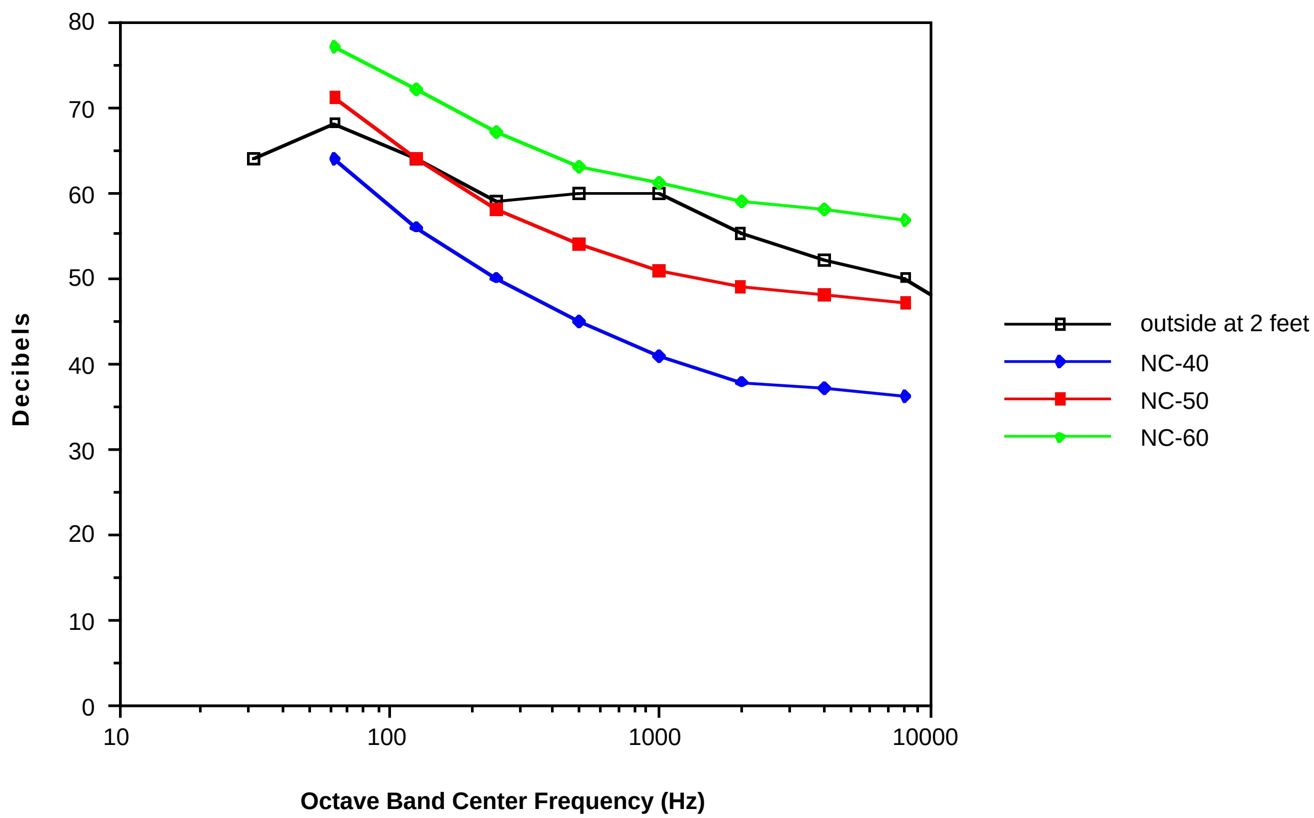

Figure 10. AEM prototype exterior noise levels at 2 feet.

Results of Prototype Animal Enclosure Module Noise Measurement Testing

Interior noise– The CFP flight system specification (FSS) requires that the sound pressure level inside the specimen chamber be less than 73 dB(A). The AEM prototype would meet this requirement as it is now written. Although the AEM octave band SPL at 125 Hz is 74 dB (which is greater than 73), the overall A-weighted SPL is 66 dB(A). This is less than the requirement of 73 dB(A). There is no current requirement for the maximum SPL in any octave band.

Exterior noise– The AEM flies in a shuttle middeck locker and as such must meet the middeck noise limits (as specified in fig. 15 in the appendix). The requirement is verified at 1 foot (as compared to 2 feet for SSF noise limits). Since a doubling of distance translates to a halving of pressure level (i.e., a 6 dB reduction) this is a significantly more difficult requirement to meet for a given dB level. The AEM prototype as tested does not meet the middeck requirement (see fig. 9 for a direct comparison).

Figures 9 and 10 compare the AEM noise as measured at 1 foot and 2 feet to the NC curves. The SSF requirement is NC-40 at 2 feet. The AEM prototype would not meet this requirement. The reduction in SPL at a doubling of distance is to 1–10 dB (and is frequency dependent) rather than the –6 dB (for all frequencies) predicted in a free field.

Animal Care Facility Testing

Ambient noise levels were measured in two animal-holding rooms of the animal care facility (ACF) at Ames (Bldg. N-236) in preparation for the rodent acoustic noise tolerance study and to determine what typical animal residence noise levels are.The results are shown in tables 11 and 12 and figures 11 and 12.

Results of Animal Care Facility Testing Noise Measurement Testing

The noise level within ACF holding rooms is less than the CFP’s on-orbit acoustic noise requirement of 73 db(A) within the specimen chamber .

The interior of the AEM prototype is significantly louder than the ACF holding rooms.

Table 11. ACF Room B-5 noise levels

Octave band	dB
31.5	65
63	56
125	59
250	57
500	53
1,000	49
2,000	<45
4,000	<45
8,000	<45
16,000	<45
Overall	71 dB
A-weighted	54 dB(A)

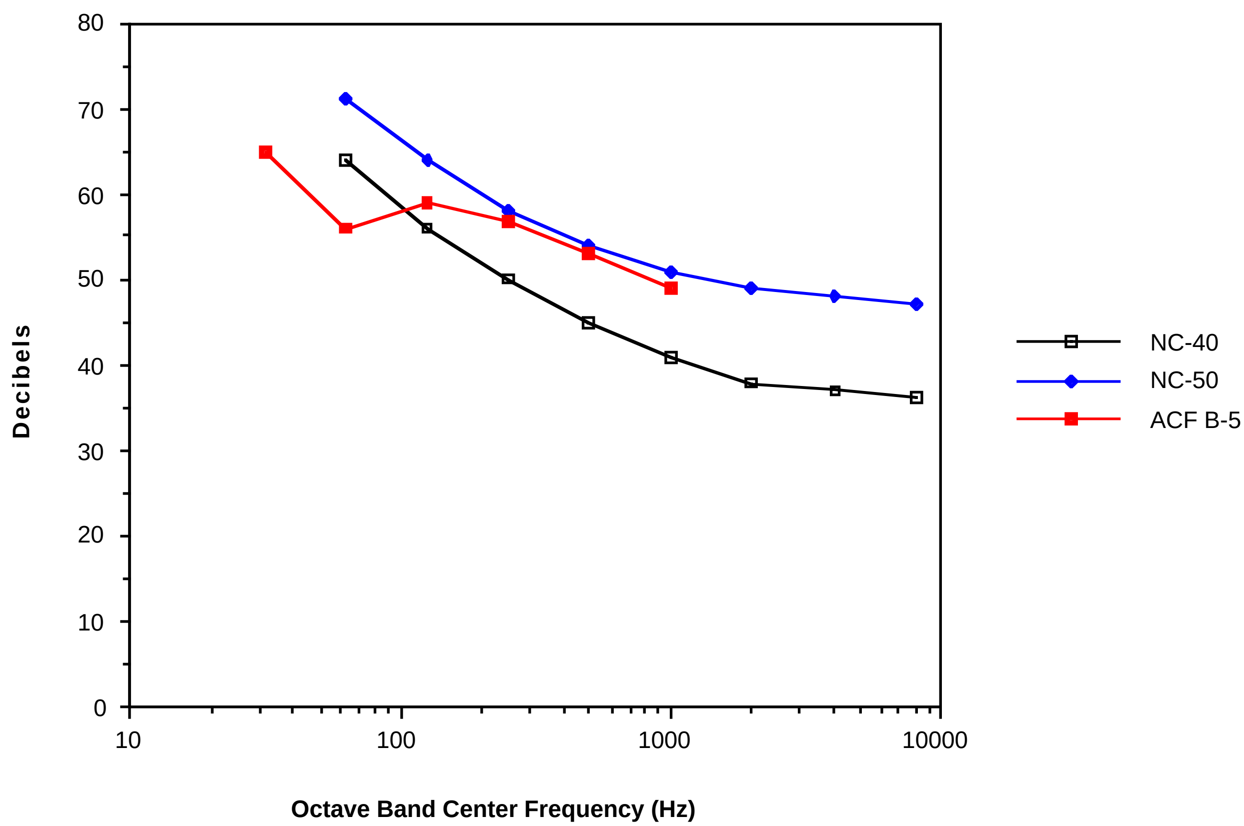

Figure 11. ACF Room B-5 noise levels.

Table 12. ACF Room E-5 noise levels

Octave band	dB
31.5	66
63	66
125	60
250	55
500	50
1,000	52
2,000	54
4,000	48
8,000	<45
16,000	<45
Overall	71 dB
A-weighted	58 dB(A)

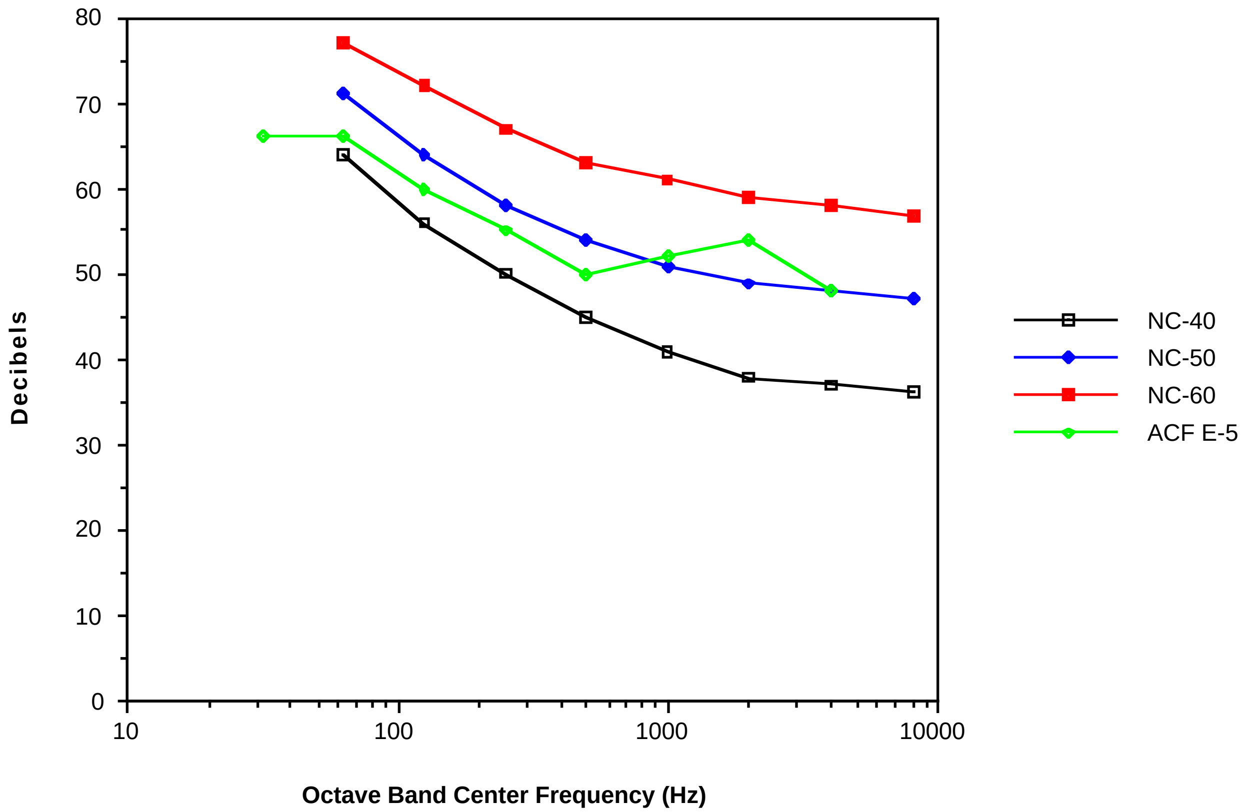

Figure 12. ACF Room E-5 noise levels.

Literature Review

Animal Enclosure Module Flight Unit Test Results

Test results were obtained (AEM Parametric Acoustic Test, Document Number X-AH--01003 dated 1/16/91) for flight AEM 001 and CAEM 101. In general, the flight units are quieter than the prototype AEM tested by the CFP, but they still do not meet the middeck requirements (fig. 13).

It is interesting to note that the background noise in the anechoic chamber in Bldg. 247 (as listed in the Special Test Procedure) is very low except for at the 63 Hz octave band. The background level at 63 Hz is 52 dB. This is within 3 dB of the overall dB level at 63 Hz (AEM and background), and therefore a subtraction should be performed by the method described previously. Since the AEM noise is generally above the limit at most frequencies, this subtraction would not have made the difference between the AEM's passing or failing.

SSF Component Noise Emissions

All SSF components must meet the NC-40 requirement. Since it is expected CFP that hardware will share many common components with SSF core systems, much can be learned from SSF component supplier activities in the areas of noise testing and control. To that end, some SSF fan characteristics are detailed herein.

Avionics Air Assembly (AAA)/Rack Essentials Package Fan

Purpose of the fan– To recirculate air within a rack for the purpose of heat exchange (via an air-to-water heat exchanger located within the rack) and to provide fire detection capability (by ensuring airflow over a smoke detector).

Characteristics of the fan (from ref. 4)–

• 20–120 cubic feet per minute variable airflow

• Fire detection system smoke detector

• Circulates air within rack through air-to-water heat exchanger

• Required by SSF program for all active racks for fire detection, alternative to cold plates for electronics waste heat removal

• Both inlet and outlet will require mufflers to meet NC-40

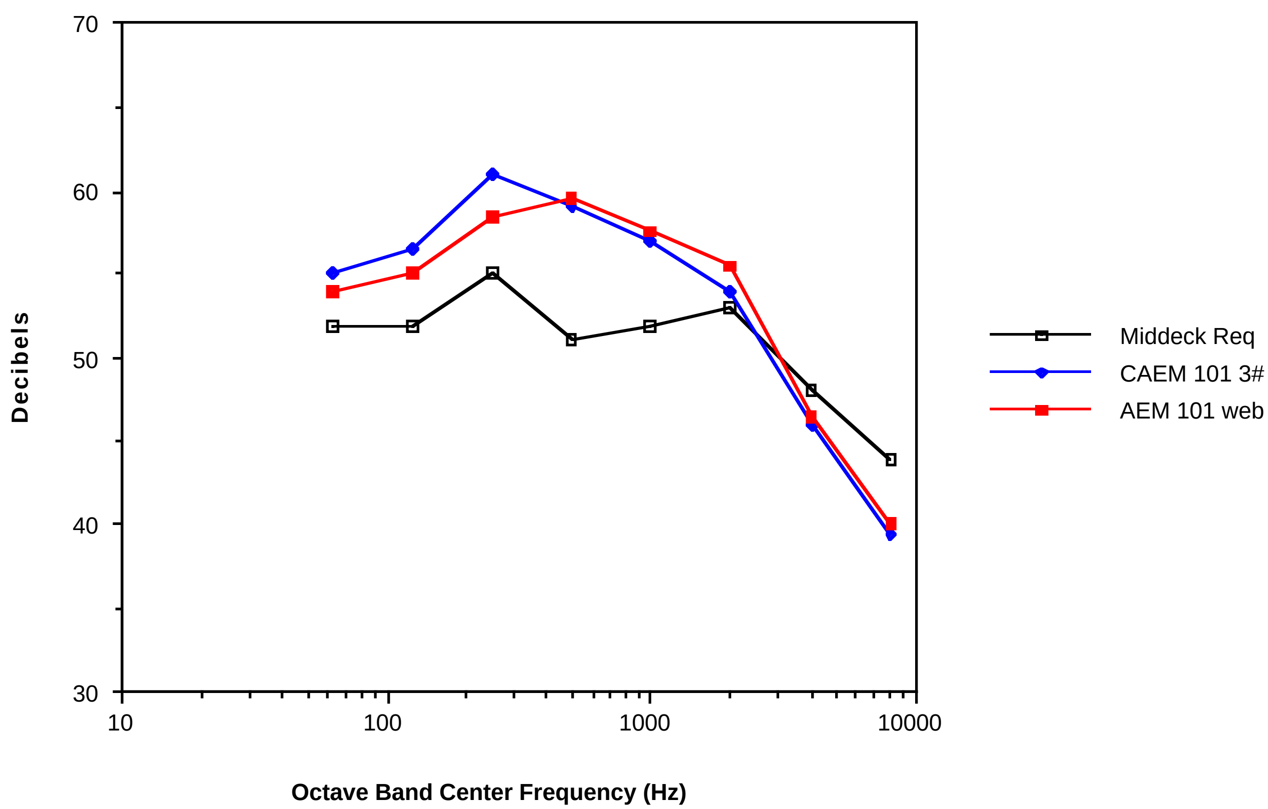

Figure 13. Flight AEM noise levels compared to middeck limits.

Discussion of AAA/REP fan– Since both the inlet and outlet of this system would be within a rack, it is unclear how the noise spectrum would affect the noise radiated from the rack. It can, however, be safely said that the AAA fan in unmuffled form is loud. In unmuffled form it does not meet NC-40 (table 13 and fig. 14). It is likely that CFP integrated systems will contain such a fan to (at least) provide the required fire detection function.

Table 13. Unmuffled duct noise levels for an SSF AAA Fan

Octave band	SPL (dB)
31.5	NA
63	44
125	50
250	57
500	63
1,000	68
2,000	65
4,000	67
8,000	68
16,000	NA

Reference 4

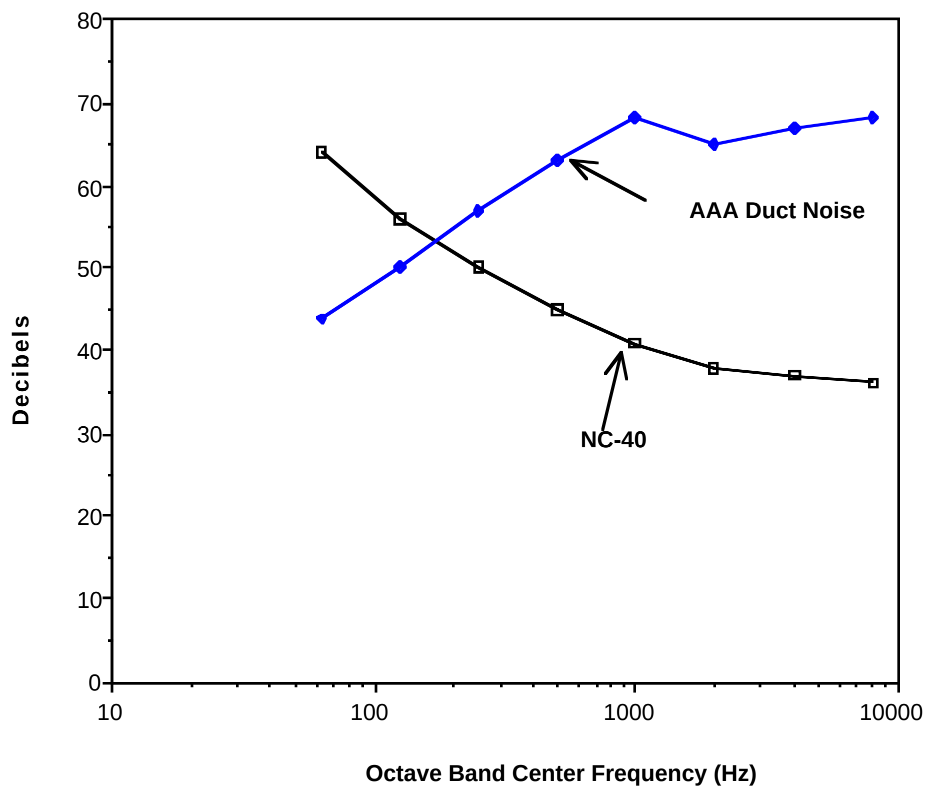

Figure 14. SSF AAA fan noise levels compared to NC-40 limits.

SSF Rack Attenuation

Many noise sources in SSF and within CFP integrated systems will be contained within standard SSF racks. These racks can provide some sound attenuation to the habitable area if there is no airborne transmission path (table 14).

Table 14. SSF rack attenuation

Octave band	IL (dB)
31.5	NA
63	7
125	10
250	11
500	13
1,000	16
2,000	20
4,000	20
8,000	19
16,000	NA

Reference 4

The higher frequencies are attenuated the greatest. A maximum of 20 dB reduction in SPL can be expected. Since some CFP noise emitters will be contained in an enclosure, the attenuation of the enclosure can be considered when budgeting noise allocations. The CFP holding unit will most likely be based on a standard SSF rack and therefore may benefit from the attenuation provided by the rack structure. The noise in the habitable area resulting from a single AAA fan recirculating air within the rack (and hence having no airborne transmission path to the crew habitable area) modified by the attenuation of a standard SSF rack would exceed NC-40 at all octave bands from 500 Hz upward.

Space Shuttle Ascent Internal Acoustic Environment

A shuttle launch is a noisy event, even when witnessed from miles away. Common sense would tell us that it must be much noisier at the launch pad. It has even been said that it is loud enough to kill birds that are unfortunate enough to be in the vicinity. What common sense might not tell us is how this intense sound propagates into the orbiter crew compartment and Spacelab module during launch (ref.5) or how loud it might be during launch in a pressurized logistics module for SSF (ref. 6). Fortunately, we can rely on previous work to get these answers. Following are all-pass measurements referenced to $P_o = 2 \times 10^{-5}$ N/m^2 (pascals).

Launch pad external noise level	150 dB (ref. 3)
Crew cabin noise level during launch	118 dB (ref. 3)
SSF element internal noise level during launch	127.5 dB (ref. 6)
Spacelab internal noise level during launch	118 dB (ref. 1)

Fortunately, the above noise levels are of short duration. Within 2 minutes the orbiter has passed through “Max Q” and the noise rapidly diminishes. See reference 1 for plots of octave band noise and overall SPL versus time for a shuttle launch.

None of the testing or analysis discussed in this report deals with the noise attenuating characteristics of facility hardware subject to an external noise field—only with the noise produced by the hardware itself. Although this is not presently an issue (the transporter has no internal acoustic level requirements except for on-orbit), it might become one if it is ever determined that the launch noise levels listed above are in any way detrimental to animal health and well being. This is because the transporter used to bring the rodents to SSF will be located in the middeck and subjected to the 118 dB launch noise environment present in the crew cabin.

Design Practices that Reduce Acoustic Emissions

• The acoustic noise power emitted by a mechanical device is a small but relatively fixed proportion of the total power of the device. Lower total mechanical power will result in lower total noise. The preferred design approach is to reduce the total mechanical power if at all possible.

• Higher frequency noise is easier to shield and absorb than lower frequency noise.

• Atmospheric absorption is negligible at all audio frequencies for systems with the dimensions typical of a manned spacecraft.

• Low frequency noise is less disturbing to humans than high frequency noise.

• Small vibrating surfaces generate less noise than larger surfaces.

• Low velocity mixing of fluid streams produces the least amount of exit noise. For low speed flows, reducing the speed by half results in lowering the sound level by 25 dB.

• Sound absorbing treatments should be applied to the inside of enclosures, not the outside.

Conclusion and Recommendations

• The project should continue to develop and maintain expertise in acoustics. This expertise should be broad and extend from theory to design, to design analysis, testing, and verification.

• The SSF NC-40 requirement should be called out explicitly in section 3 (General System/Design Requirements) of the FSS. This will give the requirement additional emphasis. Currently the NC-40 requirement is included only as part of one or more applicable documents.

• Additional statement of work tasks should be developed that include acoustic testing of components before performance verification.

• Acoustic noise budgets should be developed by the CFP prime contractor at the integrated system and system levels. These budgets should be based on an analysis (simulation or other valid method) that estimates the total noise level of each system based on probable component contributions, propagation, and attenuation of facility enclosures (SSF standard racks and facility-unique structures). The baseline NC-40 requirement should then be allocated to components.

• The FSS should be clarified as to what requirements apply to what equipment. The rodent transporter must meet middeck noise limits during its time in the middeck, and it must meet SSF requirements when it is in SSF.

• The FSS specimen accommodation requirements paragraphs, 4.1.12.2 (Rodent Habitat) and 4.1.21.1.4.1 (Glovebox Work Volume), which specify acoustic noise on-orbit within the specimen chambers are clearly wrong. A-weighting is not appropriate for the measurement and control of sound levels that are deemed health and well-being concerns for any species other than humans. These requirements need to be revised (as to dB level and frequency range) at the end of CFP's rodent acoustic sensitivity study.

Appendix

Summary of CFP Acoustic Requirements

CFP acoustic requirements fall into two categories: those that are called out explicitly in the text of the FSS and those that apply because they are stated in one of the applicable documents.

From the FSS

4.1.12.2 Acoustic Noise

4.1.12.2.1 On-Orbit

a) Steady-state acoustic noise within the Specimen Chambers during normal ground and orbital operations shall not exceed 73 dB (A) in the frequency range 20 Hz to 40 kHz.

and

4.1.21.1.4.1 Acoustic Noise

a) Acoustic noise in the work volume shall not exceed 73 dB (A) in the frequency range of 20 Hz to 40 kHz.

and

15.7.7 Acoustic Noise Isolation Tests

a) Tests shall be performed at the integrated system level to demonstrate that acoustic noise generated by the Facility does not exceed the allowable levels specified by:

(1) SSF requirements.

(2) CF Science Accommodation Requirements.

In Applicable Documents

1. SSF (Space Station Freedom Program, SS-HDBK-0001 Payload Accommodations Handbook, Volume 1: Manned Base, Draft 6, p. 5-56)

> 5.9.5.1.1 The maximum Sound pressure Level (SPL) of an individual payload shall not exceed the NC-40 curve in any octave band between 83 Hz (sic) and 8 kHz when measured two feet distant from the equipment. This requirement will protect the health of the crew and keep acoustic noise from interfering with oral communication.
>
> 5.9.5.1.2 Design Guidance The Acoustic noise of all equipment (systems plus payloads) shall not exceed the noise rating curve NC-50 of the United States Noise Standard. This means that a payload should make every effort to be as far below the NC-40 curve as possible because it takes so few equipment items at the allowable NC-40 curve to have the total noise spectrum exceed the NC-50 curve. A considerable redesign effort may be required to reduce noise levels when this situation occurs.

2. Shuttle Middeck (Shuttle/ Payload Interface Definition Document for Middeck Accommodations, NSTS-21000-IDD-MDK 3/88, pp. 4-5 and 4-7)

> 4.7.3 Payload Generated Acoustic Noise. The individual payload elements shall not emit continuous acoustic noise into the crew working/living spaces exceeding the level shown in figure 4.7.3-1 as measured one foot from the noise radiating surfaces(s). Maximum noise levels for intermittent noise generated by payload elements shall meet the limits of NASA Std. 145 in JSCM 8080.

Middeck noise limits for payloads are shown in table 15 and figure 15.

Table 15. Middeck noise limits for payloads

Octave band	dB
31.5	NR
63	52
125	52
250	55
500	51
1,000	52
2,000	53
4,000	48
8,000	44
16,000	NR
Overall	61 dB
A-weighted	58 dB(A)

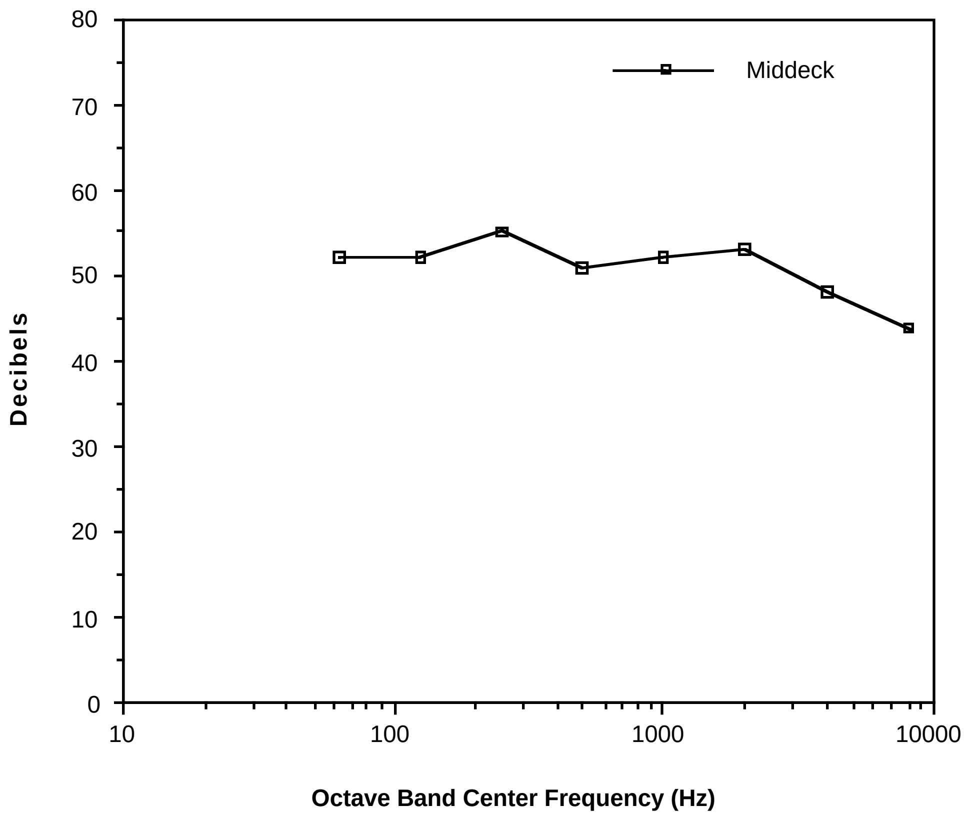

Figure 15. Middeck noise limits for payloads.

References

1. SpaceLab Payload Accommodations Handbook, SLP/2104, Marshall Space Center, Huntsville, Ala., Aug. 1985.
2. Noise and Vibration Control, Leo Beranek, ed., Institute of Noise Control Engineering, Washington, D.C., 1988.
3. Space Station Freedom Man-Systems Integration Standards, NASA-STD-3000, Rev A, Johnson Space Center, Houston, Tex., June 1991.
4. MTC Acoustic Configuration Report, D683-99085-2, The Boeing Corporation, Defense and Space Group, Huntsville, Ala., Aug. 1993.
5. Space Station Vibroacoustic Control Plan, SSP-30671, Space Station Freedom Program Office, Reston, Va., Sept. 1992.
6. Space Station Freedom Program, SS-HDBK-0001, Payload Accommodations Handbook, Volume 1: Manned Base, Draft 6, Marshall Space Flight Center, Huntsville, Ala., June 1993.

Bibliography

Aiflow Optimization in Animal Enclosure Modules, Final Report to NASA Ames Research Center, Harvey Mudd College, Claremont, Calif., June 1992.

Objective and Subjective Measures of Noise on STS-40/SLS-1, Document B, Johnson Space Center, Houston, Tex., Dec. 1991.

Shuttle/ Payload Interface Definition Document for Mid-deck Accommodations, NSTS-21000-IDD-MDK, Johnson Space Center, Houston, Tex., Mar. 1988.

Spacelab/Payloads Acoustics Working Group (SPAWG) Final Report, OSSA, NASA HQ, Washington, D.C., July 1992.

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13. ABSTRACT ***(Maximum 200 words)***

Acoustic noise emissions from the Space Station Freedom (SSF) centrifuge facility hardware represent a potential technical and programmatic risk to the project. The SSF program requires that no payload exceed a Noise Criterion 40 (NC-40) noise contour in any octave band between 63 Hz and 8 kHz as measured 2 feet from the equipment item. Past experience with life science experiment hardware indicates that this requirement will be difficult to meet. The crew has found noise levels on Spacelab flights to be unacceptably high. Many past Ames Spacelab life science payloads have required waivers because of excessive noise.

The objectives of this study were (1) to develop an understanding of acoustic measurement theory, instruments, and technique and (2) to characterize the noise emission of analogous Facility components and previously flown flight hardware.

Test results from existing hardware were reviewed and analyzed. Measurements of the spectral and intensity characteristics of fans and other rotating machinery were performed. The literature was reviewed and contacts were made with NASA and industry organizations concerned with or performing research on noise control.

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